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Oceanic Lidar

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Proceedings of a workshop held at
Goddard Space Flight Center
Greenbelt, Maryland
November 13-14, 1980

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Washington, D. C.

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Goddard Space Flight Center
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PREFACE

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PREFACE

In anticipation of the kinds of investigations that may be possible in the latter half of this decade when there are prospects for satellite-borne ocean color scanners (in addition to the Coastal Zone Color Scanner (CZCS) being considered for NOAA H or I, the Japanese and Europeans are both planning to have color scanners in orbit), NASA is considering "in situ" and airborne instrumentation which will aid in the signal interpretation of various satellite sensors. Instruments which will supplement satellite capabilities by providing data of shorter temporal and spatial scales and information about the dynamics of the upper ocean are also needed.

Understanding the oceanic processes which will affect ocean color scanner images, whether they are affected by upwelling-induced phytoplankton productivity or shoaling of the chlorophyll maximum due to internal waves, is one important goal of the Oceanic Processes Branch of NASA. Airborne, and perhaps even towed submerged Light Detection and Ranging (LIDAR) systems that are SONAR-equipped, could play an important role in helping to extend the synoptic measurement range of ships, in providing ocean truth for satellite ocean color sensors, and in helping to measure the dynamics of phytoplankton and grazing organisms. The Oceanic LIDAR Workshop was held to consider the utility of LIDAR systems to these types of ocean, color-related problems.

LIDAR technology has recently developed to the point where airborne quantitative measurements of several oceanic variables can be confidently made. These include shallow water bathymetry, oil film thickness, oceanic tracer dye concentration, and chlorophyll _a_ concentration. The latter three measurements rely heavily on using the OH stretch water Raman backscatter spectral line which is observed almost routinely in coastal and oceanic waters. In addition to the water Raman backscatter, airborne lidars have detected hydrocarbon (oil) fluorescence, "on-frequency"

backscatter from water and particles, and dissolved and particulate organic fluorescence. Some LIDAR systems are electronically configured to allow measurement of many of the variables as a function of depth, to depths equivalent to one or two attenuation lengths (20 to 40 m in waters with Sargasso Sea type clarities for blue wavelengths) even in daylight. However, airborne LIDAR has not to date demonstrated an ability to measure to depths where the oceanic chlorophyll maximum is found.

A second type of Lidar system should be considered to address the third or vertical dimension of the euphotic or productive layer of the ocean. Throughout much of the global oceans, a chlorophyll maximum is found at depths equivalent to about three attenuation lengths. While this is below the depths from which significant upwelling radiance is contributed to the Nimbus-7 CZCS signals (about one attenuation length), internal waves can vertically displace the chlorophyll maximum to within CZCS view, potentially confusing the interpretation of CZCS images. Also, in order to measure the standing crop of chlorophyll and to assess the productivity of the oceans, one must be able to measure the phytoplankton (chlorophyll) distribution/concentration to depths where about 1 percent of the surface light irradiance remains. One method that might be used to achieve this would be to tow a submerged LIDAR system two attenuation lengths below the surface, and to range-gate LIDAR returns up to the surface and down to depths equivalent to four attenuation lengths (e.g., 80m to 100m deep). By using ratios of the reflected radiances at two wavelengths (e.g., 450 and 520 nm) centered about the transparency window (480 nm), chlorophyll and attenuation coefficient estimates as a function of depth, from the sea surface to depths of 80 to 100 meters in clear water, should be attainable. Simultaneous activation of high frequency sonar soundings should permit higher trophic level organisms to be range-detected and compared to the locations of phytoplankton patches. Thus, phytoplankton and zooplankton dynamics may be addressable remotely and simultaneously for the first time, permitting a more intimate understanding of the mechanisms affecting the growth and consumption of the first two tropic levels. With such a

system, not only would one be able to quantify plankton patchiness, but with appropriate physical and chemical observations, one could begin to address ecological aspects and particle dynamics problems of the upper ocean.

Dr. Kendall L. Carder
Ocean Optics Program Manager
Oceanic Processes Branch

SUMMARY

This two day Oceanic LIDAR Workshop brought together, in a relatively rare occurrence, a group of ocean LIDAR and ocean color technologists with a selected group of scientists from the oceanographic community. Much of the first day was dedicated to presentations of the state-of-the art of several existing airborne, shipboard and laboratory ocean LIDAR systems, and of the interpretation of Coastal Zone Color Scanner (CZCS) imagery in terms of near surface phytoplankton chlorophyll abundance. Then, several working groups met to discuss needs and directions for future research, after which their reports were presented and discussed by all the Workshop participants.

My last exposure to ocean remote sensing with LIDAR was in 1978 in conjunction with an IUCRM Colloquium on "Passive Radiometry of the Ocean".[1] From this more recent workshop, it becomes clear that in 2-1/2 years, we have progressed from "gee whiz" pictures and theoretical possibilities to honest grappling with problems such as environmental signal-to-noise, strategies for meaningful ground truthing, and determining directions that will be scientifically fruitful as well as technologically fascinating. Several matters arising from the Workshop deserve individual mention.

i) Effective ground-truthing for airborne and satellite remote sensing requires sensor technology and sampling strategy comparable in sophistication with the remote sensing itself. The scales and intensity of the in situ variability must be determined such that the ground truth calibrations are averaged appropriately for the "footprint" and depth penetration of the individual airborne or satellite sensors.

ii) More basic research is required immediately on the passive and active optical properties of live and dead organic materials in sea water.

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1. Gordon, H.R. (editor). 1980. Ocean Remote Sensing Using Lasers, NOAA Technical Memorandum ERL PMEL-18, 200pp.

iii) While research into the stimulation of chlorophyll fluorescence at 685 nm by multiple wavelength excitation and the stimulated flourescence of the plant pigment phycoerythrin are fascinating, the "pay-off" to marine ecologists is most likely to occur with the remote sensing of phytoplankton chlorophyll by multiple band ocean color measurements. The two overwhelming advantages are the increased depth penetration that results from avoiding the use of red light, and the elimination of having to resolve the variation in fluorescence yield per unit chlorophyll pigment that results principally from the recent light history of the phytoplankton.

iv) The proposal to mount a LIDAR system on a towed underwater vehicle is definitely of interest to marine ecologists, but it must be emphasized that the ecological significance of obtaining data in three dimensions of chlorophyll abundance resolved down to a scale of approximately 1 m^3 is predicated on simultaneous and similar data for zooplankton, presumably obtained by high frequency (approximately 10^6 Hz) sonar. The scientific problem to be addressed through information on their mutual correlations is that of grazing interactions.

v) Remote sensing of chlorophyll abundance from airplanes or satellites, and to a lesser extent from a towed underwater vehicle, will provide marine ecologists with improved knowledge of spatial variability in the oceans. However, there is no successful biological analog to a moored current meter that routinely provides physical oceanographers with long time series of currents, temperature and salinity. The LIDAR and acoustics sensors envisioned for a towed underwater vehicle would be ideal sensors for a moored system to provide long time series information on the abundance of

phytoplankton and zooplankton at any point in the ocean. There is a definite need for such a system.

Kenneth L. Denman
Institute of Ocean Sciences
Canadian Department of Fisheries and Oceans

Acknowledgements

NASA gratefully acknowledges the valuable contributions that the presentations of Drs. Raymond Smith, Donald Leonard, Michael Bristow, Reginald Exton, Wayne Esaias and Frank Hoge made to the success of the LIDAR Workshop. The logistical and organizational support provided by Suzanne Bassford is especially appreciated as is the help that David Stowell provided in preparation of this document.

SECTION I. ABSTRACTS OF PRESENTATIONS

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I.1 INTRODUCTION

Abstracts of the talks given by developers and users of oceanic LIDAR systems are shown in the order of presentation.

I.2 PHYTOPLANKTON PATCHINESS AND THE COASTAL ZONE COLOR SCANNER (CZCS) VALIDATION EFFORT

R. Smith, Scripps Institute, La Jolla, CA

Complementary and contemporaneous ship and satellite (Nimbus-7-CZCS) bio-optical data from the Southern California Bight and surrounding waters have been and are being obtained in order to make a quantitative assessment of the spatial and temporal variability (patchiness) of chlorophyll in these waters.

CZCS data have been processed to reveal variations in the concentration of phytoplankton pigments. A three-week time series of chlorophyll maps, obtained from CZCS imagery of the Southern California Bight show the quantitative variation of chlorophyll for this region during this period. Similar data, covering a time period of 18 months will be processed in the near future.

These data are being used to increase our understanding of mesoscale biological patterns and processes in productive coastal waters. We intend: to study the physical and biological processes leading to this chlorophyll

References

Smith, R. C. and W. H. Wilson (1980), "Ship and Satellite Bio-Optical Research in the California Bight", Proceedings of the COSPAR/SCOR/I VCRM Symposium, Oceanography from Space, Venice, Italy, March 26-30.

variability; to assess seasonal primary productivity (using chlorophyll as an indication of phytoplankton biomass) for the entire Southern California Bight region; to investigate the relationship of chlorophyll variability to fish recruitment and marine mammal distributions.

I.3 RAMAN TEMPERATURE SPECTROSCOPY IN THE OCEAN

D. Leonard, Computer Genetics Corp., Wakefield, MA

This paper describes the application of Raman scattering to the remote sensing of subsurface temperature, salinity and attenuation profiles. The theoretical basis of the method is discussed, including an estimation of the potential of the measurement technique in terms of accuracy and depth penetration as a function of laser power and other system parameters. Both laboratory and field experiments, conducted by the author over the previous years, are described. The current overall status for the Raman technique is reviewed. An overall survey reference for this work (which contains 40 references) is D. A. Leonard, et. al. Applied Optics 18, 1732 (1979).

Theoretical Basis

The physical basis of the measurement can be described by the following: (a) liquid water exists in at least two forms, monomer and polymer; (b) the two forms are in chemical equilibrium as a function of temperature; (c) the O-H Raman stretching frequency is significantly different for the monomer and polymer forms, (d) the relative concentration of monomer vs. polymer can be determined from the Raman spectrum, and thus the temperature can be

inferred. The measurement is thus a direct measurement based upon an intrinsic temperature-dependent property of the water molecule itself.

Salinity information is obtained as a non-linear perturbation to the basic water Raman spectrum, i.e., the addition of salt makes certain regions of the spectrum appear hotter. Attenuation profiles are obtained by using the Raman signal as a normalizing factor either to itself at successive depths or to other signals being measured such as fluorescence.

Estimation of Potential

Since the Raman scattering cross-section for water is known, the performance of a Raman LIDAR subsurface temperature measurment system, if not limited by interferences, can be exactly calculated as a function of water turbidity, laser power and other system paramters (see Above Reference). Environmental interferences are expected to be dominated by volume depolarization producing a temperature uncertainty of $0.1^{o}C$ per diffuse attenuation length of depth.

Field Experiments

Field experiments have obtained laser Raman temperature data in a variety of natural waters including the coastal waters of Massachusetts, Nova Scotia, Florida and the Bahama Islands and open ocean waters of the North Atlantic, the Mediterranean and the Equatorial Pacific. The results of these experiments in general have demonstrated $1^{o}C$ temperature accuracy and data retrieval down to 4 diffuse attenuation lengths of depth. Recent experiments in the Dalhousie University 10 meter high stratified tank are reported in which a temperature gradient is measured under controlled conditions.

I.4 CORRECTION OF LASER FLUOROSENSOR SIGNALS USING WATER RAMAN RETURN

M. Bristow, EPA Las Vegas, NA

The airborne laser fluorosensor measurements can now be corrected for interferences introduced by the presence of waterborne dissolved and particulate matter in the water column. This represents a significant advantage over the passive multispectral imagery approach of mapping surface water chlorophyll a. Large variations in the optical transmission of surface waters can occur over short horizontal distances because of changes in the concentrations of suspended materials. These changes in concentration result in large variations in the depth of penetration of the laser beam, and produce fluctuations in the received fluorescence signal that are often unrelated to the algae concentration. This interference has been successfully eliminated by monitoring the concurrent water Raman emission. This Raman signal is a property of the water alone and variations in its intensity are an indicator of changes in optical transmission. By taking the ratio of the chlorophll a fluorescence signal to the water Raman signal, a new chlorophyll a indicator is obtained that is independent of these changes (Bristow et al, 1979).

The laser fluorosensor uses a downlooking, pulsed laser transmitter to simultaneously excite fluorescence and Raman emissions from the chlorophyll a and water, respectively. The chlorophyll a fluorescence emission occurs at 685 nm, whereas the water Raman emission occurs at 560 nm when excited at 470 nm. These emissions are collected by a telescope receiver, which is imaged on the laser excitation spot on the water surface. The fluorescence and Raman emission bands are then isolated using a beam splitter and optical interference filters. The fluorescence and Raman signals are detected by two gated photomultipliers, displayed in real time on an oscilloscope, and concurrently digitized and recorded on magnetic tape for later analysis.

The system has been successfully operated under full daylight conditions at an elevation of 1,000 feet above the water surface. The laser emits 300-kW, 200-nsec wide pulses with a beam divergence of 10 mrad and at a repetition rate of 1 pulse per second. At an average ground speed of 80

feet/second, a series of 10-feet diameter sampling points is produced, approximately 80 feet apart, below the aircraft flight path. For the above described conditions, the system is capable of resolving, with good sensitivity, surface water chlorophyll a concentrations down to 0.1 µg/l or less in the presence of a high solar background. Because of significant day-to-day and place-to-place variations in the ability of algae to convert incident radiation into fluorescence emission, calibration of the airborne fluorescence data in terms of the equivalent chlorophyll a concentration is achieved by making several concurrent ground truth chlorophyll a determinations on grab samples from a small number of key reference sites located under the sensor flight path.

System evaluation has been conducted over a single, well-defined 10-km flight line located in the Las Vegas Bay region of Lake Mead, Nevada, where concurrent ground truth measurements were taken at and between 14 sampling buoys located under the aircraft flight path. Excellent agreement has been achieved between the airborne and ground truth measurements after the fluorescence data have been corrected for variations in surface water optical transmission using the Raman normalization technique. In addition, the airborne data have been shown to be highly reproducible when the measurements are repeated over the same flight path a short time later.

It has also been shown that the water Raman return can be used to monitor changes in the optical attenuation coefficient of surface waters. This was demonstrated by the high correlation observed between the airborne water Raman data and the reciprocal of the beam attenuation coefficient data obtained from concurrent ground truth measurements.

References

Bristow, M., D. Nielsen and R. Furtek, 1979. A Laser-Fluorosensor Technique for Water Quality Assessment. Proceedings of the 13th International Symposium on Remote Sensing of the Environment.

Research Institute of Michigan, Ann Arbor, Michigan. April 23-27, 1979, pp. 397-417.

I.5 THE MULTIPLE LASER EXCITATION APPROACH TO LASER FLUOROSENSING

By W. Esaias, NASA-LaRC, Hampton, VA

A technique and instrument for remote measurements of both chlorophyll a concentration and plankton color group diversity was developed at Langley Research Center under the Airborne Laser Oceanographic Probing Experiment (ALOPE). Four dye lasers operating at 454, 539, 598, and 617 nm differentially excite chlorophyll flourescence according to accessory pigment content and interpigment energy transfer efficiencies. Flourescence is monitored at 685 nm from each of the sequential excitations. Based on laboratory measurements of fluorescence excitation cross section spectra for a variety of algal species, the fluorescence returns from the four excitations can be apportioned to contributions from four algal color groups: golden brown, green, blue-green, and red algae. For marine environments especially, relative differences between golden-brown (diatoms and dinoflagellates) and green (chlorophytes and nanoplankton) are very important in understanding the nature and dynamics of phytoplankton communities and their role in the marine ecosystem.

The accuracy of all in-vivo fluorescence techniques is dependent upon knowledge of the fluorescence cross section (σ) and attenuation coefficients at the excitation and emission wavelengths, in order to estimate chlorophyll concentration.

Airborne LIDAR technology has advanced to the stage where the flight instruments are as accurate as conventional shipboard in-vivo fluorometers, and are limited by the same variability of fluorescence cross-section within the populations. The Wallops Airborne Oceanographic LIDAR (AOL) recently demonstrated an excellent relationship between fluorescence and chlorophyll pigment concentration (r^2 = .94, n = 10) over a range of

0.2 -5 µg/l near the mouth of Chesapeake Bay. The mean absolute error between measured values and those predicted by the regression was 10.2%.

Since fluorescence cross-sections of phytoplankton populations change with environmental conditions, chlorophyll pigment concentrations should be determined at a number of sea truth points during each field experiment for best results. For example, using only laboratory estimates of σ, with no chlorophyll sea truth, the ALOPE instrument has provided estimates of total chlorophyll accurate to within a factor of 2 - 3 over the range of 5 - 25 µg/l (provided independent measures of attenuation coefficient, such as could be made using a water Raman detector). ALOPE estimates of color group percent composition are relative rather than absolute measurements, and the resolution of the technique is of the order of 10%-20%.

It is impossible to distinguish between spatial variations of chlorophyll concentration and spatial variations in using single wavelength in-vivo techniques alone. Multiwavelength excitation techniques can at least distinguish that component of the variability arising from color-group-dependent variations of the cross section. Since this is a ratio technique somewhat independent of chlorophyll concentration, a multiple wavelength technique can provide a second measure of phytoplankton spatial variability and "patchiness" which can be of great benefit in marine ecosystem dynamics research.

Farmer, F.H., et. al. 1980. Remote Sensing of Phytoplankton Density and Diversity Using an Airborne Fluorosensor, pp 151-167, in Advanced Concepts in Ocean Measurements for Marine Biology, F.P. Diemer, F.J. Vernberg, and D.Z. Mirkes, eds. Univ. South Carolina Press, Columbia, 575 pp.

Yentsch, C.S., and C.M. Yentsch 1979. Fluoresence Spectral Signatures: The Characterization of Phytoplankton Populations by the Use of excitation and Emission Spectra. J. Mar. Res. 37, 471-488.

I.6 LASER REMOTE SENSING OF SEDIMENT LOAD AND ALGAL PIGMENTS

R.J. Exton, NASA-LaRC, Hampton, VA

A laboratory study was conducted to study the major spectral features (Mie, Raman and fluorescence) of laser-excited natural water bodies. The lasers employed include an argon-ion, a pulsed Nd:Yag and a pulsed N_2 ultraviolet laser. Surface samples were analyzed in a 1-meter tank using an optical multichannel analyzer (OMA) having a resolution of 2 nm. The results indicate that for single wavelength excitation, the optimum wavelength is about 515-520 nm in order to obtain the greatest penetration into the water column and to avoid spectral interferences between the Raman and fluorescence signals. By exciting in this region, the OMA can easily record and separate the Raman scattering caused by water from the fluorescence of the algal pigments, phycoerythrin and chlorophyll. Using the Raman scattering from water as an internal standard, the Mie/Raman ratio was shown to be proportional to sediment load. Phycoerythrin fluorescence[1] was also identified and can be measured in an analogous method to that used for chlorophyll[2]. The spectra also showed the presence of the underlying fluorescence due to dissolved organic matter and spectral unfolding of this component showed a reasonable correlation with dissolved organic carbon.

I.7 AIRBORNE OCEANOGRAPHIC LIDAR MEASUREMENTS

By Frank E. Hoge
Wallops Flight Center, NASA

Reviewed in this paper is the recent progress in the airborne LIDAR measurements of (1) ocean wave profiles and resulting spectra, (2)

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[1] C. S. Yentsch and C. M. Yentsch, J. Mar. Res. 37, 471 (1979).

[2] M. Bristow, D. Nielsen, and R. Furtek, Proc. 13th Inter. Symp. Remote Sensing of Environment, Apr. 23-27, 1979, Ann Arbor, MI.

bathymetry, (3) crude oil film thickness, (4) tracer dye concentration, (5) attenuation coefficient by depth-resolved Raman, (6) dissolved organic matter by fluorescence, (7) suspended solids via Mie scattering, and (8) chlorophyll through single wavelength excitation of the usual 685 nm fluorescence emission. The first four techniques are reasonably well established and are briefly reviewed. The remaining techniques are discussed in depth. Available 381 nm depth-resolved Raman backscatter data show the high potential for this technique for extraction of water transmission properties. Dissolved organic matter, fluorescence spectral waveform, and time-series data obtained during synoptic mapping missions in the German Bight region of the North Sea are given. Spectral channel-to-channel calibration techniques are briefly reviewed. Finally, the Mie scatter and chlorophyll data obtained during overflights in the Chesapeake Bay/Atlantic Ocean regions are discussed. In particular, the excellent stability and repeatability of the AOL data are demonstrated with the chlorophyll and Raman data obtained on two successive, overlapping flightlines. Possible airborne LIDAR techniques to remove the specular reflection component of the airborne Mie scatter data are considered.

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F. E. Hoge and J. S. Kincaid, 1980: "Laser Measurement of Extinction Coefficients of Highly Absorbing Liquids," Applied Optics 19, No. 7, 1143-1150.

F. E. Hoge and R. N. Swift, 1980: "Oil Film Thickness Measurement Using Airborne Laser-Induced Water Raman Backscatter," Applied Optics 19, No. 19, pp. 3269-3281.

F. E. Hoge and R. N. Swift, 1980: "Airborne Oceanographic LIDAR (AOL) Data Acquisition Modes and Recent Results," in Proceedings, Ocean Remote Sensing Using Lasers, Howard R. Gordon, Ed., NOAA Technical Memorandum ERL PMEL-18, Seattle, Washington.

F. E. Hoge and R. N. Swift, "Absolute Tracer Dye Concentration Using Airborne Laser-Induced Water Raman Backscatter," (Manuscript submitted).

SECTION II. DISCUSSION GROUP SUMMARIES

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SECTION II. DISCUSSION GROUP SUMMARIES

II.1 LIDAR APPLICATIONS TO PHYTOPLANKTON DYNAMICS

Chairman: Dr. John Steele, Woods Hole Oceanographic Institution

In considering patchiness and productivity, larger measurement scales than those addressable quasisynoptically from ships and smaller scales than those presently addressable from satellites are necessary. Zooplankton-phytoplankton interactions produce measurable changes in concentrations on temporal scales of the order of hours to days and on spatial scales from meters to tens of kilometers.

Using existing (non-LIDAR) technology, towed "Batfish" types of platforms (containing CTD's, fluorometers, and optical particle counters) "porpoise" through a vertical cycle each 1/2 km in towing distance, missing the smaller patches. On the other hand, the CZCS satellite system is limited as follows: (1) it cannot operate at low altitudes, thus is weather restricted, (2) the large CZCS "footprint" (800 m x 800 m minimum) makes surface validation from ships difficult because plankton and suspended particle patchiness occur in three-dimensions, and (3) the vertical structure in temperature, chlorophyll, and zooplankton (using SONAR) cannot be addressed.

While airborne LIDAR systems can address the "scale" and part of the vertical structure problems, they presently cannot provide accurate enough temperature data (now only $\pm 1^{o}$ to $\pm 3^{o}$ C) nor have they been shown able to measure zooplankton concentrations. The present systems can probably provide particle concentration measurements to depths of 20m to 40m (one to two attenuation lengths for blue light) in clear water (this has not been tested), but the vertical maximum in the chlorophyll concentration usually occurs at depths equivalent to three or four attenuation lengths.

Inclusion of the chlorophyll maximum is undoubtedly critical to measurements of the standing crop of chlorophyll (phytoplankton) and to estimates of water column primary productivity.

Towed, submerged LIDAR systems should be able to address the vertical structure of chlorophyll and the zooplankton/phytoplankton interaction problems if the "fish" is also SONAR-equipped. The addition of a thermistor chain to the tow line would permit accurate temperature information to be gathered as well. The maximum effective SONAR range for zooplankton is 5 to 20 m, while that for LIDAR fluorosensing of chlorophyll is 10-20 m maximum due to the large attenuation at 685 nm. A two-wavelength backscatter approach such as is used for CZCS determinations of chlorophyll (e.g., 440 nm and 520 nm) may extend the LIDAR chlorophyll sensing range to perhaps 40 m in clear water. Conceivably then, if the tow body were towed at 20 m depth, a cylindrical swath of coverage for LIDAR and SONAR of as much as 40 m diameter might be sampled. A return track tow at 50 m could provide a 10 m overlap with the previous sample volume and still extend the measurements to 70 m. For krill and fish, the SONAR range could be extended by using lower frequencies so that a cylindrical sampling volume of perhaps 20 m diameter could be investigated in a single pass, matching the clear water sampling volume addressable with LIDAR. This, in most cases, would permit the entire mixed layer and euphotic zone to be sampled in one pass, including the chlorophyll maximum layer.

One potential contribution that simultaneous LIDAR determinations of chlorophyll and particle concentration may provide is a measure of the "quality" (chlorophyll/cell) of chlorophyll. A change in the "quality" of chlorophyll may reflect upon the condition (e.g., log growth, senescence) or "robustness" of the phytoplankton populations.

Additional laboratory work is needed to better understand the fluorescence cross-section of phytoplankton from the various color groups under a range of environmental conditions. The utility of attempting to characterize

phytoplankton "in-situ" in terms of their color group is as yet unclear. However, the significance of phycoerythrin-bearing organisms as primary producers has recently been touted. Extension of the important work of R. Exton in attempting to quantify phycoerythrin fluoresence should be encouraged, as LIDAR permits us to measure phycoerythrin fluorescence (570 nm) and chlorophyll fluoresence (680 nm) simultaneously (stimulated by light at 530 and 430 nm, respectively).

II.2 LIDAR APPLICATIONS TO PHOTOCHEMISTRY

Chairman: Dr. Oliver Zafiriou, Woods Hole Oceanographic Institution

Both the dissolved and particulate fluorescers in the oceans appear to give rise to detectable LIDAR signals of sufficient magnitude to obscure the Raman returns from even abundant constituents, such as sulfate (R. Exton, person communication). This situation holds potential both for advancing our study of organic photochemistry in the oceans and for potential LIDAR applications. Further studies of the sources and decay processes of the fluorescers and the closely related "Gelbstoffe" in seawater and natural waters will enhance our knowledge of the chromophores, which may be of major importance in marine photoprocesses. Conversely, if the behavior of these materials were better understood, for the shorter wavelength signals (probably originating in dissolved materials) the strong LIDAR return would be more amenable to interpretation.

A second area in which LIDAR data may be useful to marine photochemists is in the determination of optical attenuation lengths. Although Jerlov and others provided rough maps of such properties, our detailed understanding of light penetration at different wavelengths into the sea is poor; thus, our ability to model depth dependence quantitatively is restricted by an inadequate data base. It would be especially valuable to have more reliable estimates of light penetration in the near UV range, as such measurements are extremely sparse. For example, attenuation lengths at 337 nm would be quite useful; as such information may be gathered also for other

purposes in LIDAR applications, it is important that the data are actually stored and made available in useful form (e.g. not simply applied in real time to normalization factor calculations) for photochemical interpretation.

A third area of overlap between basic studies and LIDAR applications is in the determination and understanding of fluorescence decay times of fluorescers: the fluorescence lifetime is related to the chemical structure involved and the physical environment of that structure on the one hand, and is thus of interest to the marine photochemist. The lifetime also has practical consequences for range-gated LIDAR in that signal decay times longer than about 5 ns can be expected to degrade the performance of range-gated systems using range increments on the scale of one meter or more.

II.3 LIDAR RADIATIVE TRANSFER AND SIGNAL INTERPRETATION

Chairman: Dr. Howard Gordon, University of Miami

Although LIDAR fluorescence signals from chlorophyll and water Raman have correlated quite well with chlorophyll (directly) and suspended solid concentrations (inversely), respectively, the radiative transfer process involved is not well understood. The attenuation coefficient involved in the process appears to be a hybrid of diffuse attenuation "K" and beam attenuation "c". The actual coefficient probably depends strongly on the geometry of the viewing system and on the "turbidity" of the water. Radiative transfer modelling, "in-situ" measurements of ocean optical properties, and short-pulse, range-gated LIDAR measurements should be sufficient to understand the physics of the problem. Then the deconvolved LIDAR fluorescence measurements as a function of depth can be compared to "in-situ" chlorophyll determinations.

To improve the present accuracy ($\pm 1^{o}$ C) of water-Raman-inferred temperatures using polarization spectroscopy, a better understanding of the

depolarization effects of ocean particles is needed (depolarization of 1% gives a 1^{0} C error in temperature). Measurements of the Mueller matrix components in the near-forward and near-backward directions of various suspensions of monospecific phytoplankton and other single component types of ocean particulates and their input to radiative transfer models of LIDAR-induced Raman spectroscopy may be sufficient to permit improvements in Raman-temperature accuracy by partially correcting for particle depolarization effects.

At present, it is unclear what the lower limit of detectablity with existing LIDAR systems is for chlorophyll, dissolved organic carbon, and total suspended solids. None of these systems have operated over clear, open-ocean water as yet. This information is critical to any evaluation of LIDAR utility for assisting in the CZCS validation effort, since CZCS determinations as low as 0.05 µg/l chlorophyll have been made and are typical of mid-oceanic values. Only a few LIDAR chlorophyll values as low as 0.1 µg/l have been made; most flights have been made over more productive waters.

It is clear that given a better understanding of the oceanic radiative transfer functions of LIDAR systems, they will have great utility if applied to mixed layer dynamics and CZCS validation, by measuring suspended particle concentrations and fluorescence as a function of depth. The LIDAR measurement of three-dimensional diffusion rates of fluorescent dye and the growth, advection, and dissipation of phytoplankton patches are examples of mixed-layer dynamics presently addressable by LIDAR systems.

In future systems, the limited depth range from which chlorophyll fluorescence can be detected because of the large water attenuation coefficient of red light (685 nm) can probably be circumvented by using two low-attenuation laser wavelengths (e.g., 440 nm and 520 nm). Reflected signals at each wavelength can be range-gated and then ratioed, to extract a

"color-derived" chlorophyll concentration as a function of depth. A similar spectral comparison without depth resolution is presently being used to extract chlorophyll information from CZCS data. The advantage of this technique is that after traveling through 10 meters of "Jerlov Type I" (clear ocean) water, there is about 70 times as much blue (440 nm) and green (520 nm) light remaining as red (685 nm) light, given equal source radiances. Radiative transfer modelling of this approach together with color reflectance spectra measurements of representative phytoplankton groups should be pursued in addition to modifying an existing LIDAR system to allow range-gating simultaneously at two wavelengths.

Mounting a range-gated LIDAR system on a submerged, towed vehicle or "fish" and configuring the optics to scan radially about the tow direction would result in a cylindrical sampling volume with a diameter as large as 60 to 100 m for clear waters (Jerlov types II or I) using the two-color technique suggested above (assuming a nominal range of two attenuation lengths). For phycoerythrin fluorescence (=580nm) the sensing diameter would be about one-half the two-color chlorophyll diameter, and for chlorophyll fluoresence (=685nm) it would be about 10 m. In the near field, chlorophyll fluorescence measurements could be compared with two color chlorophyll determinations for calibration purposes.

II.4 LIDAR TECHNOLOGY: PRESENT AND FUTURE

Chairman: R. J. Exton, NASA/Langley Research Center

LIDAR AIRCRAFT

One of the most important considerations in the design of an aircraft LIDAR system is detection of the weak signals. For this reason, it appears that photomultipliers will be required in all systems in the near furture. In this regard, the Airborne Oceanographic LIDAR (AOL) with its 40 photomultipliers represents the only viable way of attaining complete spectra at this time. Other systems are also in use today using filters and photo-

multipliers for specific wavelengths (constituents), but it is highly desirable to obtain complete spectra in order to properly evaluate the effect of spectral interferents. An updated AOL should include increased resolution (factor of 2 possible with grating change) and wavelength tunability in the laser (planned for the future).

In the plenary session, a desire of the user community was expressed for a simplified, inexpensive version of the AOL which could be used on a more routine basis. One possibility for such a system using a helicopter was proposed which could also be used to obtain sea surface truth at selected locations. Using the low altitude capability afforded by helicopter, it may be possible to employ a less sensitive, solid state detection system which could be coupled with a spectrometer to yield the entire spectrum in the integrated signal mode.

LIDAR SHIPBOARD

For shipboard measurements, an AOL type configuration can certainly be employed with a submerged window for entering the water column. For the integrated signal mode, an Optical Multichannel Analyzer (OMA) configuration could easily be used. The laser/OMA technique is presently being investigated at the Langley Research Center for use on shipboard and also for use on a towed submersible (fiber optic transmission and reception).

RANGE GATING

Range gating in order to obtain depth information on an oceanographic parameter is technically feasible today. The AOL system is presently capable of obtaining time resolved data in selected channels. It should be recognized, however, that range gating, in practice, is not an easy task and places severe constraints on the available signal. In addition, the data collection from many simultaneous channels presents a problem in data recording and storage. However, components suitable for the gating task are commercially available. Such equipment, lasers with $\sim$3 ns pulse

widths, good gain photomultipliers with ~1 ns risetimes, and nsec rate transient digitizers, will allow water column measurements with about one meter vertical resolution.

WAVELENGTH OPTIMIZATION

The question of the optimized wavelengths to be employed in laser excitation experiments was posed and the response involves several answers. Obviously, the selection between a number of available, fixed laser wavelengths depends on the parameters to be sensed. For a single wavelength system, there was a consensus among the group that the laser output should be located in the range 515 - 520 nm in order to avoid spectral overlaps and to maximize the penetration of the light into the water. If a two-color system is considered, it would be possible to choose wavelengths which would allow better definition of algae color groups in a manner analogous to the four-color Airborne LIDAR Oceanographic Probing Experiment (ALOPE) system. It was also proposed that Mie returns from a two-color system with wavelengths matched to the CZCS visible bands may allow chlorophyll measurements to be made with depth, a task which may be impossible to do with measurements made at the much attenuated chlorophyll fluorescence wavelength of 685 nm. Finally, it was suggested that the ultimate research LIDAR would involve a dynamically tuned laser coupled with a real-time spectral coverage of the returned signal. With such a system, a trained observer could logically probe the optimum excitation conditions for unfolding a variety of oceanographic parameters.

ACCURACY

The accuracy associated with LIDAR measurements are difficult to quote at this time. The absolute accuracy is determined by the sea-truth techniques which are well known. It was felt, however, that the reproducibility of the chlorophyll fluorescence signals obtained by the LIDAR methods are considerably better than the present-day laboratory methods. In this sense, improvements in the absolute accuracy of LIDAR chlorophyll

measurements will track, one-to-one, the improvements made in the sea-truth calibration data.

Regression analysis of laboratory Raman returns indicates that Raman supression compares with the diffuse attenuation coefficient within ±10%. Mie/Raman normalized returns compare with suspended particulate matter (SPM) values within ±15%. SPM calibration curves will change with particle size and index of refraction (e.g., differ for clay- or phytoplankton-dominated hydrosols,) so interpolation between ground truth data is best for heterogeneous particle regions.

FUNDAMENTAL STUDIES

From the standpoint of absolute measurements, there are several areas where additional studies are needed to define the measured parameters. The most important of these is the variation of the fluorescence cross-section of algae with light history, temperature and nutrient effects. Although these effects have previously been delineated in the literature, a reexamination of these effects with the methods and specific wavelength employed in LIDAR sensing would appear in order.

With respect to range gating, a concurrent study of the radiative lifetimes of phycoerythrin, DOM, and chlorophyll is required to establish the limitations on time-resolved spectra of these constituents.

Finally, the measurements of phycoerythrin require the development of a laboratory method of extracting and quantifying this pigment before correlations with remote data are possible. In this connection, it would be desireable for the oceanographic community, to indicate the importance of phycoerythrin to oceanographic sensing in general, and more specifically, the role played by phycoerythrin in photosynthesis.

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APPENDIX A. AGENDA

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OCEANIC LIDAR WORKSHOP AGENDA
NOVEMBER 13 & 14, 1980
GSFC, BLDG. 26, RM 200

NOVEMBER 13, 1980

0830	Registration	
0850	Introductory Remarks	K.L. Carder
0900	Phytoplankton Patchiness and the CZCS Validation Effort	R. Smith
0930	Raman Spectroscopy in the Ocean	D. Leonard
100-	Correction of LIDAR Signals Using the Water Raman Return	M. Bristow
1030	B R E A K	
1045	Measures of Spatial Distributions and Species Diversity Using Laser Techniques	W. Esaias
1115	Laser Remote Sensing of Marine Sediment Load and Algal Pigments	R. Exton
1145	Fluorescence Measurements Using the Airborne Oceanographic LIDAR	F. Hoge
1215	L U N C H	
1330	Plenary Session: Discussion of Issues Raised by Speakers	
1430	B R E A K	

1445 DISCUSISON GROUPS:

a. LIDAR Applications to Phytoplankton Dynamics

b. LIDAR Applications in Photochemistry

c. LIDAR Radiative Transfer and Signal Interpretation

d. LIDAR Technology: Present and Future

1645 Plenary Session: Discussion Group Summaries

1715 A D J O U R N M E N T

NOVEMBER 14, 1980

0830 Welcome

0845 Plenary Session: General Discussion of Group Summaries to Include Airborne and Submerged LIDAR Capabilities and Accuracies Required by Scientific Disciplines, and Deliverable (Present and Future) by LIDAR Technology.

0930 Discussion Groups: Utility of Present and Future LIDAR Systems for Oceanographic Research

1045 B R E A K

1100 Plenary Session: Discussion Group Summaries

1200 A D J O U R N M E N T

APPENDIX B. WORKSHOP PARTICIPANTS

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15. Supplementary Notes

16. Abstract

This is a report on the Oceanic Lidar Workshop held at the NASA Goddard Space Flight Center on November 13-14, 1980. This meeting provided an opportunity for oceanographers to interface directly with Lidar instrumentation specialists to consider future instrument concepts that would measure ocean temperature, chlorophyll, sediment and "Gelbstoffe" concentrations in three dimensions on a quantitative, quasi-synoptic basis. Included are abstracts of presentations on Coastal Zone Color Scanner chlorophyll imagery, laser-stimulated Raman temperature and fluorescence spectroscopy, existing airborne Lidar and laser fluorosensing instruments, and their accuracies in quantifying concentrations of chlorophyll, suspended sediments and "Gelbstoffe." Summaries are included from discussion groups on Lidar applications to phytoplankton dynamics and photochemistry, Lidar radiative transfer and signal interpretation, and Lidar technology (present and future). An executive summary is provided by Dr. Kenneth Denman.

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primary productivity		
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